AN ANALYSIS OF HEAVY TRUCK OCCUPANT PROTECTION MEASURES

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ABSTRACT

Analysis of truck crash data shows that the majority of truck occupant fatalities occur as a result of rollover or frontal collisions. A large proportion results from single-vehicle crashes and about one third of fatal crashes involve ejection of the truck driver from the cab. Stronger cab structures to provide adequate occupant survival space, the use of stronger doors and side inflatable tubular structures to prevent ejection, more forgiving interior surfaces, air bags, and seat belts are all possible means of reducing occupant injury.

This paper provides a status report on a current effort to mitigate crash injury to large truck occupants. It presents a detailed survey of the current state-of-the-art in occupant protection countermeasures and their effectiveness, an analysis of U.S. truck crash data with an overview of occupant injury modes, and concludes with a description of a current effort intended to quantitatively estimate the benefits of implementing these countermeasures for the U.S. road system.

INTRODUCTION

Using the Trucks Involved in Fatal Accidents (TIFA) and the General Estimates System (GES) databases it can be seen that, over the five-year period from 1995 to 1999, annually about 376,000 large trucks (Gross Vehicle Weight Rating (GVWR) over 10,000 lbs) were involved in a traffic crash on U.S. roads. These crash involvements resulted in considerable loss in terms of deaths, injuries (ranging in severity from incapacitating (A injuries) to complaint of pain (C injuries)), and property damage. Although the lighter vehicles involved in the crashes suffered the most damage, the adverse effects to the truck and its occupants are also significant and merit investigation for the purpose of reducing their severity and costs. Annually, about 744 truck occupants are killed and 29,000 are injured in traffic crashes. Considering only truck drivers, an average of 633 drivers were killed and 24,000 were injured.

This paper provides a status report on a current effort to mitigate crash injury to large truck occupants. The paper begins with a detailed survey of the current state of the art and discusses various occupant protection countermeasures and their effectiveness in mitigating the severity of post-crash injuries. The paper then presents an analysis of U.S. truck crash data with an overview of occupant injury modes. (The focus of the crash data analysis is restricted to the driver rather than all occupants of the truck.) The paper concludes with a description of the current effort intended to quantitatively estimate the benefits of implementing these countermeasures for the U.S. road system.

TRUCK OCCUPANT PROTECTION RESEARCH

Truck Crash Characteristics

Seiff (1985) identified some of the major characteristics of truck crashes and a follow up study, Seiff (1989) documented the improvements in truck safety both in terms of reduced crash rates (on a per mile traveled basis) and the decreased injuries and fatalities to both car and truck occupants in truck involved crashes.

- Large trucks (weighing over 10,000 lbs) are involved in about 13% of all fatal highway crashes. Only about 18% of these fatalities are truck drivers themselves, 82% of the fatalities were pedestrians or occupants of other vehicles involved in the crash. (1976-1983 data, Seiff (1985))
- About 72% of fatal truck crashes are multi-vehicle crashes, 15% are single vehicle crashes and 8% are trucks hitting pedestrians or cyclists.
- A vast majority (about 70%) of truck occupant fatalities occurs in single vehicle crashes. Rollover is involved in 60% of truck occupant

fatalities, ejection in around 35%, extrication in about 22%, and 16% of cases involve fires.

Cheng (1996) more recently explored the issue of truck crash characteristics, through in-depth studies of 68 fatal truck crashes. The author stated that the statistical characteristics of these 68 cases closely approximate those of FARS, with the exception of one crash type – that in which the truck strikes a fixed object after rollover. The authors' opinion is that the difference in this case results from the fact that FARS consistently underestimates this category of crashes.

From the case studies, fatal truck crashes can be classified into the following categories:

- Head on collisions: These involve collisions between trucks traveling in opposite directions and make up about 22% of fatal multi-vehicle truck crashes. In these cases, the collision is usually significantly offset or a sideswipe. High closing speeds are observed in this crash type, which results in significant intrusion into the driver side of each tractor.
- Rear end collisions: These involve a faster moving truck striking the rear of a slower moving or stationary truck, mostly with full contact and constitute about 52% of fatal multi-vehicle truck crashes. Significant damage and intrusion is caused to the cab of the striking tractor due to height mismatch between the striking tractor frame and the struck trailer frame.
- Collisions with fixed objects: These crashes generally involve boulders, buildings, guardrails, etc. Significant or total cab destruction can result if the struck object is large such as a bridge pier or building. If smaller obstructions are struck, the severity of the crash usually results from rollover. The author presents FARS (1975-89) data showing that these two crash types (striking fixed objects without and with rollover) constitute respectively 20% and 18% of fatal truck crashes.

Crashes with rollover can themselves be further distinguished into the following types.

- 90º rollover without subsequent collision: In this case there is minor cab deformation and intrusion.
- 90º rollover with subsequent collision: There may be significant cab damage and intrusion in this case and the collision after the rollover is the most harmful event.
- 180º rollover: In this case, the tractor finally rests on its roof. Flat bed trailers are much more likely to experience 180º rollovers than van trailers. There is extensive destruction of the cab in the vertical direction, and the roof may be forced down to the seat level, totally compromising survival space.

Berg (1997) undertook a comprehensive study of truck usage statistics and truck crash figures in Germany from 1970–1995. The paper presented a general overview of crashes involving commercial vehicles, based on a study of 400 crashes. Information about test and simulation studies of commercial vehicle crash testing was also included. The author stated that collisions of trucks against the rear of other commercial vehicles were an important but neglected subject of study. These kinds of crashes accounted for 29% of commercial vehicle crashes in Germany and were very severe to the truck experiencing the frontal impact. There was significant structural incompatibility between the two vehicles in this case leading to high cab deformations even in low speed crashes and a high percentage of severe truck occupants injuries or fatalities.

Overall, a large majority (~70%) of fatal truck crashes involves only a single vehicle – the truck itself. Further, three crash modes or a combination of these, dominate all fatal crashes. These three are (i) rollovers, (ii) collision with fixed objects, and (iii) collision with another vehicle. A significant proportion (55%) of fatal crashes are associated with rollovers. Furthermore, whenever rollover appears with combination of other modes, the rollover itself frequently is the most harmful event to the driver.

Causes of Injury to Truck Occupants

While the aforementioned studies investigated the common characteristics of truck crashes, a number of studies considered the issue of the relationship between these characteristics and the injury modes or mechanisms observed in the occupants of the truck.

Neilson (1987) reviewed literature and data relating to heavy truck usage on the European road system. The major causes of injuries observed in truck crashes were ejection from the cab or crushing of the cab structure. The principal crash types, in which ejection was observed, were frontal impacts (even at low speeds) and rollovers. Ejections through the front windscreen were most common. Significant crush of the cab structure leading to occupant injuries occurred mostly in collisions with other large trucks or with fixed objects such as roadside structures.

Eggleman (1987) studied in detail 136 truck crashes, from both the U.S. and Europe, in which the truck occupant was injured. The study too, noted the importance of ejection and entrapment (cab crush) but added a third cause of injury, namely, impact with the interior components that may occur with or without intrusion due to cab crush. The most common part of the body injured was the head with 55% of all injured occupants suffering head injuries. Injuries to arms and legs were second most common though they were generally not as serious. The author noted that truck cabs offer relatively little protection (compared to passenger automobiles) in the form of energy absorbing crush space and thus are more prone to intrusion or entrapment type injuries.

Seiff (1985) using US crash data identified rollover and ejection (occurring either separately or together) as the cause for the greatest number of truck occupant fatalities. Rollover was involved in 59% of driver fatalities, with ejection found in 34.5%. Driver extrication (indicating crush or entrapment type injuries) was necessary in about 22% of fatal crashes. Fire was involved in 16% of truck driver fatalities. Many of the fatal crashes involve more than one of the previously mentioned injury mechanisms.

Berg (1997) also identified ejection and cab crush as primary factors in driver injury. Of all the ejected occupants 50% were killed and 33% of all occupants that were pinned in the cab were also fatally injured. In comparison only 7% of occupants who were not ejected or pinned suffered fatal injuries.

Of all the interior cab objects causing injury, the steering wheel is the most common, indicating the steering wheel is a target for design improvement efforts. Other conspicuous areas are the dashboard and foot/leg area. The author also mentions that in 2% of the cases the retention system itself was the cause of the injury. Given that very few trucks included in the survey were fitted with seat belts and that the usage of these is also very low, this strongly indicates a need for further improvements in the retention technology.

Ranney (1981) noted some specific patterns in the injury mechanisms relating to interior impacts. Impact with the steering assembly was the most common cause of injury followed by impacts with the instrument panel, doors and windows, and finally windshield and roof. Also, impacts with the steering assembly caused the most severe injuries, followed by the relatively infrequent injuries due to the roof.

Injuries to the head are most common, followed by upper extremities and thorax. Injuries to the abdomen and thorax are almost exclusively caused by the steering assembly and are typically the most severe. Heavy trucks differ from the rest of the truck population in that steering assembly impacts result more commonly in chest injuries (as opposed to the head) and can be quite severe.

Grandel (1989) also studied the interior of truck cabs. The goal of this study was to examine exterior and interior cab deformations in truck crashes and their relation to occupant injury. For this purpose data from 100 truck crashes (involving trucks with payload > 3.5 tons) in which occupants were injured were analyzed. The results of the first 33 crash investigations are reported in this paper.

- Truck/Truck crashes play the largest role in occupant injury. Car/Truck crashes are also found to be dangerous for truck passengers because the impact can lead to dangerously unstable driving conditions that cause overturning or secondary impacts. Single vehicle crashes like overturning did not lead to above-average injuries. Also, for truck/truck crashes, head on collisions were not as dangerous as rear-end collisions, which caused more fatalities and serious injuries (to the occupant of the truck that strikes the rear of the other vehicle) due to the strength and stiffness mismatch between truck cabs (relatively soft) and rear structures (stiff).
- Cab deformation: Even relatively minor deformations of the cab exterior (less than 20 cm) can cause serious or fatal injuries to occur, but only as a result of truck occupants being ejected from the cab. Deeper deformations (between 20 and 40 cm) cause serious injuries more often and fatalities less often. Deep deformations (above 40 cm) often cause serious injuries and fatalities.
- Interior impacts: The steering assembly most often causes injury to drivers. The steering wheel/steering column usually comes up together with the foot/leg area causing serious injuries especially to the legs and chest. Interior components that suffer damage (like pillars) do not generally cause injury, whereas parts like the steering column that do not deform cause much greater injury, because the deformation acts as an energy dissipation mechanism to soften the impact of the occupant against the component

Current U.S. Truck Occupant Safety Requirements

In the U.S., trucks are required to have certain occupant safety equipment by the Federal Motor Vehicle Safety Standard (FMVSS). FMVSS 209 and 210 require heavy trucks to have seat belts assemblies and seat belt assembly anchorages the same as is required for passenger vehicles. FMVSS 208, occupant crash protection, requires that trucks over 10,000 lb. have either a complete passenger protection system that meets the requirements of section 5 or a Type 1 or Type 2 seat belt assembly that conforms to FMVSS 209. (Refer to CFR Title 49, Chapter V., Section 571.208, S4.3.2. for more complete information.)

Truck Occupant Crash Protection Countermeasures

The subject of interior crash protection has received significantly more attention for automobiles than for commercial vehicles. The experience gained from these studies forms a good foundation for designing improved truck occupant protection systems and will be briefly surveyed here, before focusing on the literature relating to heavy trucks.

Hobbs (1980) provided an in-depth analysis of injury patterns and mechanisms for car occupants. Gabler (1991) studied the safety performance of cars with respect to interior head impacts using sled tests with Free Motion Head Form (FMH) dummies. The study concluded that even as little as one inch of padding on the interior surfaces most involved in head impacts can reduce the head injury criterion (HIC) by as much as half. Scott (1995) studied car-truck collisions and the improvements in injury outcomes possible using interior countermeasures. Hollowell (1996) presented results from car crash tests against both other cars and deformable or moving barriers. The principal conclusion of the study was that airbags prevent serious head or chest injuries in all but the most severe crashes, but that lower extremity injuries are more common and require improvements in protection systems. Digges (1998) studied rollover crashes and demonstrated that seat belts are the single most effective countermeasure in preventing injury (by preventing ejection and reducing interior impacts) in such crashes.

Occupant protection systems can be distinguished into systems that require the occupant to actively adopt their use, such as wearing seat belts or helmets etc., and those that are inherently present in the vehicle such as airbags, energy absorbing steering columns, padding of interior structures etc. These are sometimes referred to as active and passive systems respectively. Active systems (especially safety belts) have the disadvantage that use of the system is not always assured, thus often rendering them ineffective. Evans (1989) compared the effectiveness of the two most popular passive and active safety measures in passenger automobiles, namely air bags and seat belts. Seat belts reduce the risk of fatality by preventing ejection of the occupant and reducing the severity of impacts with interior objects, while air bags reduce the chance of injury due to impacts with interior components primarily in frontal collisions. Based on crash data, the author has calculated that seat belts are 77±6% effective in reducing occupant fatality. Air bags alone (without the use of seat belts) are 18±4% effective in reducing occupant fatality. Combined use of seat belts and air bags is estimated to provide an added 5% reduction in fatalities over the use of seat belts alone.

Seiff (1985 and 1989) presented an analysis of methods for reducing the injury toll of truck crashes, through both crash prevention and using post crash occupant protection countermeasures.

- The most important aspect in preventing injury to truck occupants is seat belts. Seat belt use in heavy trucks increased from 6% in 1982 to about 33% in 1987. The author suggests that improvements in seat belt design other restraint systems are the most important area for study.
- Protection from post crash fire.
- Cab interiors free from sharp and hard objects, improved design of steering wheel rim and column.
- Improved cab design providing crash space and means of escape after crash.

Clarke (1994) and De Coo (1994) dealt respectively with U.S. and European efforts to improve truck occupant protection. Both studies used detailed analysis of truck crashes combined with crash testing to estimate the achievable improvements in truck occupant injury outcomes. De Coo (1994) concluded that a 60% reduction in injury measures is possible through the use of seat belts alone and a further 21% reduction is possible with the addition of airbags.

Clarke (1994) analyzed crash data from 182 case summaries of fatal heavy truck crashes from a 1990 NTSB study to develop computational crash simulations and representative crash pulses to research occupant dynamics, and truck cab interior crashworthiness.

Analysis of crash data revealed three principal types of crashes; rollover, collision with fixed object, and collision with other trucks. In the majority of the collision cases the principal impact was frontal. Fatal head on collisions with other trucks or with fixed objects are usually characterized by high closing speeds. Fatalities caused by collision with the rear end of another truck occur over a wide range of speeds and involve occupant compartment intrusion due to the cab of the striking truck, contacting the frame of the struck truck. Rollovers occur in nearly 50% of the sample of cases studied. 180^{o} rollovers were generally not survivable due to crush of the occupant compartment. 90^{o} rollovers usually allow sufficient survivable space. Approximately 22% of the analyzed crashes did have sufficient occupant survival space.

There is considerable agreement among all studies of truck interior safety that occupant restraint systems are the most effective measure in reducing injury severity and fatality rates. Cheng (1996a and 1996b) used crash reconstruction and simulation studies to analyze the effectiveness of occupant restraint systems. Three cases of seatbelt usage were investigated, a three-point seat belt, a lap belt, and an unrestrained occupant. In rear-end collisions, the shoulder belt was shown to be effective in limiting forward excursion of the upper body and limiting head impact with the steering wheel and the roof. In rollover crashes, the seat belt was less effective in preventing impacts with the roof. As expected, lap belted and unrestrained occupants suffered higher impact forces.

Kubaik (1997) presented a detailed dynamic testing based analysis of the effectiveness of a three point seat belt coupled with an air bag in heavy trucks. Tests were conducted using a High Impulse Generator (HYGE) slide on a 50th percentile male dummy. Four scenarios were considered: exclusive use of seat belt, exclusive use of air bag, use of airbag and seat belt and unrestrained occupant. Since the maximum number of injuries and fatalities are observed for unrestrained occupants, the data collected for those were treated as a baseline (100%) and all other observations were normalized with it. Tests were conducted twice for each scenario to avoid variations in dynamic testing.

The results obtained are summarized in Table 1. The author presents the following discussion of the test results:

Table 1
Comparison of
Occupant Restraint System Effectiveness

	Seat belt/ Airbag	Airbag	Seat Belt	Unrestrained
Head injury Criteria (HIC)	83.7	94.1	148.4	100.0
3 ms Resultant Chest Acceleration	72.5	70.8	81.2	100.0
Chest Deflection	96.1	97.6	87.4	100.0
Chest Viscous Injury	76.7	84.9	68.3	100.0
Positive Neck Shear	25.2	91.0	814.2	100.0
Negative Neck Shear	43.1	54.3	41.7	100.0
Neck Tension	64.1	67.3	137.8	100.0
Neck Compression	1.0	84.2	2.6	100.0
Neck Flexion	23.9	68.5	335.3	100.0
Neck Extension	30.7	51.3	27.5	100.0
Right Femur Load	35.5	87.8	52.7	100.0
Left Femur Load	65.1	111.1	80.4	100.0

- Unrestrained Occupants: Excessive displacement of the lower extremities occurred resulting in high femur loads. Also, the occupant's chest contacted the steering wheel causing the column tilt mechanism to rotate forward, allowing the dummy's head, right shoulder and right forearm to break through the 0.25-inch polycarbonate windshield, causing maximum injuries and ejection.
- Seat Belt only: The seat belt restrained the occupant's torso and lower extremities, lowering chest accelerations and femur loads, but allowed forward displacement of the head to continue, resulting in increased moment about the neck. In addition, the occupant's head contacted the steering wheel hub. This resulted in high HIC, positive neck shear, and neck tension and neck flexion injuries.
- Air Bag only: Air bags protected the head and the upper torso, reducing, HIC, chest accelerations and neck loads, with the exception

of neck compression due to the mass of the body pushing into the bag. It also allowed for greater forward chest and lower extremities displacement resulting in high femur loads.

- Seat Belt and Air bag: Simultaneous use of both components limited occupant's forward excursion and reduced the occupant injury level to a minimum.

Simon (2001) studied the potential benefit of 100% use of seat belts using an in-depth study of 403 truck crashes in France. (See Table 2.)

In order to evaluate the correlation between crash violence and injury level, the author defined factors such as EES (Equivalent Energy Speed), Delta V, and crash speed. These factors take into account all the relevant details, such as crash speeds, type of crash, and deformation of the vehicle. Formulae for the evaluation of these factors are given in the paper. The author tried to find a correlation between EES and injury level suffered.

Table 2
Distribution of Casualties in Trucks with a Breakdown by Truck Crash Types in France

	Crashes	Fatalities	Seriously Injured	Slightly Injured	Unhurt	Total Involved
Car to Truck	190	0	0	8	199	207
Truck to Truck	49	9	12	25	46	92
Truck with Obstacles	43	5	5	25	12	47
Truck in rollover	121	10	12	72	39	133
Total	403	24	29	130	296	479

Three main types of injury causation mechanisms are identified: (i) Intrusion: where an external object or the crushed cab frame causes injury to the passenger, (ii) Projection: where the body of the passenger impacts a object or surface within the cab, and (iii) Ejection.

Simon (2001) described the effect of using seat belts in each of these injury mechanism cases (see Table 3):

- Intrusion: For front to rear impact, seat belts can prevent or reduce injury to the upper portion (chest or head) of the body, but has no impact on the lower portion (legs, abdomen). For a belted person, the intrusion has to be in line with the person for injury to occur. For rollovers, the use of seat belts prevents injury as long as the roof crush is not directly above the occupant. The seat belt would be effective in all other cases.

- Projection: Projection is the most common form of injury and according to the author use of seat belts would reduce or prevent injury in all cases. In cases of minor injury, the injury can be avoided altogether and in case of severe crashes having high value of ESS, the injury can be reduced in all cases.

- Ejection: The author states that ejection is the most dangerous mechanism, which is most common in rollover cases. The author distinguishes two types of rollovers, counter-clockwise and clockwise. The counter-clockwise is the more dangerous of the two as the driver is closer to the ground. Seat belts again provide the most practical means of preventing ejection and reducing injury.

Table 3
Injury Causation Mechanisms for Each Crash Type

	Unhurt	Intrusion	Projection	Ejection	Other	Total
Car to Truck	199	1	5	0	2	207
Truck to Truck	46	25	19	1	1	92
Truck with Obstacles	12	10	17	5	3	47
Truck in rollover	39	9	71	13	1	133
Total	296	45	112	19	7	479

Simon (2001) used statistical models and formulae to predict injury to belted drivers with EES being the critical factor determining risk of injury. All these models suggest a lesser risk of injury in all cases for a belted driver over small to medium values of EES.

Based on these results, the author concluded that use of seat belts would avoid fatalities in about one-third of the cases, and would avoid serious injury in one-third of the cases. Primarily, these gains are in crashes between trucks, in rollover or frontal impacts or in frontal impacts with fixed objects. Potential effectiveness is due to the reduction of projection or ejection of the occupant. (See Tables 4-5.)

Table 4
MAIS Distribution Without and With Seat Belt for Each Crash Type

Type	Belt Use	Unhurt	Slightly Injured	Seriously Injured	Killed	Total
Car to Truck	None	199	8	0	0	207
	Belted	204	3	0	0	207
Truck to Truck	None	46	25	12	9	92
	Belted	60	15	11	6	92
Truck with Obsta-cles	None	12	25	5	5	47
	Belted	30	11	3	3	47
Truck in roll-over	None	39	72	12	10	133
	Belted	93	33	2	4	133

Table 5
Expected Gains with Belt for Each Injury Causation Mechanism

	Belt Use	Unhurt	Slightly Injured	Seriously Injured	Fatally Injured	Total
Intrusion	None	0	16	15	14	45
	Belted	2	16	16	11	45
Projection	None	0	102	8	2	112
	Belted	75	36	0	1	112
Ejection	None	0	5	6	8	19
	Belted	11	6	1	1	19

Simon (2001) indicated that in only one out of 479 cases would the chances of injury increase if the occupant were wearing a seat belt. The author noted the low usage of seat belts in Europe, with reported usage among truck drivers in France being as low as 1.5%.

Current Research

A number of studies address current efforts and the future directions that these efforts are likely to take to achieve improved heavy truck crashworthiness and occupant protection.

Rossow (1995) discusses post crash safety measures. Rollover and ejection present the most serious risks for truck occupants. Seat belts offer the most protection against those. Barrier crash testing at 30mph has shown that the use of advanced restraint systems may make survivable many crashes previously thought to be unsurvivable. The advances in restraint systems likely to provide the greatest benefits are seat belt pretensioning and the use of airbags. The use of new seat integrated belt systems that prevent movement of shoulder belts relative to the suspended seat, a major source of irritation for many truck drivers, may improve the usage rates of seat belt systems.

In rollover type crashes, the lack of survival space is the major cause of fatalities, and cab structural crashworthiness becomes an important issue. The author estimates that 27% of rollover crashes are survivable with the use of restraints whereas about 42% are unsurvivable, and the remaining cases may be survivable with improvements in cab structural strength. The majority of the unsurvivable crashes are 180^{o} rollovers in which cab deforms in the vertical direction to the belt line and severely compromises the survival space. 90^{o} rollovers are much less severe and more survivable. For unrestrained occupants, most of whom are ejected through the doors or windshield, the author discusses the FMVSS 206 regulations covering door latches and hinges and the FMVSS 212 windshield mounting and retention requirements.

Sicher (2000) documents a study that is particularly relevant to the current effort. This paper describes an effort to improve occupant crash protection for army truck occupants by using off–the-shelf technology available in commercial and passenger cars and trucks.

The restraint system developed for the High Mobility Multipurpose Wheeled Vehicle (HMMWV), a light tactical combat truck used by the army had the following characteristics:

- A strong head restraint for rear end crashes.
- A modern 3-point symmetrical seat belt mounted directly on the seat.
- Seat belt forces are applied at optimal positions on the occupant
- Reduced slack through use of pretensioners
- Improved lateral restraint larger side bolsters, supplemental shoulder belt and improved seat geometry.
- Anti-submarining seat bottom that was strong enough to withstand drop testing.
- Optimal seat belt geometry and rate dependent foam.

All this technology was modular and was essentially off-the-shelf, i.e. available in commercial restraint systems. The system was tested using drop tower vertical testing.

Desfontaines (2001) discusses a comprehensive study of truck safety, coordinated by the European Centre for Studying Safety and Analysing Risks (CEESAR), involving partners with unique expertise. These include universities, research labs, truck manufacturers, truck operators etc. The study emphasizes quickly integrating improvements into current practice by involving users in the entire system.

One of the important components of this study is a quality database of large truck crashes, to form the basis for assessing the efficacy of implemented safety improvement measures and to direct future studies in choosing technologies.

Another component is the High Safety Concept Vehicle (HSV), a sort of 'laboratory on wheels' concept truck developed by Volvo with partnership of all its major component suppliers. The truck contains all the state-of-the-art active and passive safety measures that may be used in heavy trucks in the near or distant future. This concept will help in choosing the most efficient technology improvements that can be integrated into commercial products.

Desfontaines (2001) also describes a systematic analysis method used to assess the efficacy of each new technology using statistical information.

- The CEESAR database of large truck crashes is used for an in-depth study of all the relevant crash cases and to determine injury causing mechanisms and relevant countermeasures.
- For each technology, a sample of relevant crashes is chosen.
- Crash reconstructions are carried out (using PC Crash software) to better understand the causes and effects of each crash.
- The next step (often the most difficult) is to quantify the effect each technology has on reducing the physical parameters of the crash (such as crash energy etc.).
- The crashes are again reconstructed to account for the protective effect of the new technology.
- The results obtained from the reconstructions are used to evaluate the effectiveness of each new technology in avoiding crashes or reducing injury.
- A more conventional substitute method that relies on accumulated experience and observations concerning crashes and their consequences (injuries caused, etc.), is also used in parallel to estimate improvements.

Sukegawa (2001) describes experimental research done in truck driver protection in Japan. 'The Guidelines for Frontal Crash Test of Heavy Duty Trucks' have been formulated in Japan, and all trucks are tested to meet these specifications. These trucks are equipped with safety features such as: three point seat belts (with pretensioner) for driver as well as occupant, side-door beams, impact absorbing steering wheel and column, airbags, softer instrument panels and a secure survival space

The paper further discusses areas in which research is being done to protect truck drivers. One of these is the type of chest and abdomen injury suffered by truck drivers that are often fatal or serious. These injuries are unique to truck drivers because of the size and position of the steering wheel. Research is being done to develop new evaluation techniques for chest and abdomen injuries. One of the concerns is the accuracy of the chest displacement meters used. The meters are used only on one chest rib and the measurements are accurate only when the steering wheel impacts that particular rib, whereas they are quite inaccurate if the wheel impacts other ribs. Sukegawa (2001) has shown that much more accurate readings can be obtained if stress measurements are obtained from multiple numbers of ribs of the dummy. The author suggests more accurate injury criterion, including those to soft tissue (called Viscous Criteria (VC)), and states that there are a large number of cases in which the driver is trapped inside the cab and an emergency rescue team is called to extricate the driver from the cab as soon as possible. The author suggests measures such as improved cab construction customized for better rescue performance, with improved and standardized door frame designs so that rescue teams can easily open the cab door, improved front panels and instrument panels that offer more survival space and are easier for rescue teams to manipulate.

Carra (2001) discussed a data collection measure initiated by NHTSA. This is the 'Large Truck Crash Causation Study' (LTCCS). Its goal is to determine the factors associated with large truck crashes, to develop countermeasures to reduce the probability of large truck crashes and to reduce the severity that do occur. The study is limited to crashes that involve at least one large truck and at least one fatality or serious injury. Data are being collected using the NASS (National Automotive Sampling System) CDS (Crashworthiness Data System). Cases in the study are sampled from 24 NASS CDS sites around the country. In addition to very detailed data on the circumstances of each crash, the LTCCS data includes information on driver injury similar to the NASS CDS file. Data collection begins in Spring 2001; preliminary analysis begins in Fall 2003

COUNTERMEASURE BENEFIT EVALUATION

The University of Michigan Transportation Research Institute (UMTRI) is currently conducting an effort to evaluate the benefits of applying various occupant protection countermeasures in the U.S. road system. As part of this effort, a detailed analysis of truck-involved crashes on the U.S. road system has been undertaken.

Crash Data Analysis

Publicly available crash data were surveyed to identify the major factors associated with truck driver injury. There has been relatively little focus on the crashworthiness of trucks or injury mechanisms for truck drivers in traffic accidents. Accordingly, the crash data available on truck driver injuries do not provide much detail on the nature of the injuries or how they were sustained. While the NASS CDS supplies detailed information on injuries to passenger vehicle occupants, (e.g., type of injury, body region, and vehicle contact point), there is no comparable data for truck occupants. The Large Truck Crash Causation Study, conducted by FMCSA and NHTSA, will include NASS-like injury detail for truck occupants, but those data will not be available for analysis until Fall 2003 or 2004.

For the purposes of the present study, crash data from two sources were analyzed: the Trucks Involved in Fatal Accidents (TIFA) study from the Center for National Truck Statistics at the University of Michigan Transportation Research Institute, and the General Estimates System (GES) file compiled by the National Center for Statistics and Analysis of the National Highway Traffic Safety Administration. The TIFA file surveys all medium and heavy trucks (GVWR > 10,000 lbs) involved in fatal crashes in the United States. Candidate truck cases are identified from NHTSA's Fatality Analysis Reporting System (FARS) file, police reports are acquired for each crash, and UMTRI researchers survey drivers, owners, operators, and other knowledgeable parties about each truck. For some years of data, some limited sampling was done to reduce the number of cases processed. The result is a near-census file that provides the most accurate identification available of large trucks involved in fatal crashes. The TIFA survey collects a detailed description of each truck involved, as well as data on the truck operator and a variable on the truck's role in the crash modeled on a similar variable in the GES file.

The General Estimates System (GES) file is a complementary data set to the NASS CDS file mentioned above. GES is a nationally representative sample of police-reported traffic crashes. It includes all motor vehicles involved in traffic crashes, not just large trucks. GES data are coded from police reports selected through a complex sampling system.

A set of analytical data files has been developed for the present analysis. While the GES file provides the best estimates of traffic crashes nationally overall, it is known to underestimate the number of crashes involving a fatality. Accordingly, in this study, all counts of fatalities and injuries in <u>fatal</u> traffic accidents are taken from the TIFA file, while statistics on <u>non-fatal</u> crashes were determined from the GES file. The combination of TIFA and GES data provides the most accurate coverage of truck crash involvements covering all crash severities: fatal, injury, and property damage only.

Five years of crash data has been combined in this analysis. Combining multiple years of crash data improves the accuracy of the analysis, particularly when considering a relatively narrow subset of the crash population, such as truck driver injury. Traffic crashes are subject to random annual fluctuations; combining several years aids in damping out the random noise and revealing underlying relationships. In addition, the GES file is a sample file, and therefore frequencies estimated from the file have an associated sampling error. Combining several years of data helps to reduce the error.

The tables show average annual frequencies or percentages for the five years of data used. Estimates taken from the TIFA file are shown exactly, since the TIFA file is virtually a census and provides the most accurate data available on fatal crashes involving trucks. Frequency estimates from the GES file are rounded to the nearest thousand, to reflect the sampling error associated with the estimates derived from GES. All totals and percentages are calculated before the rounding is done.

In this study, all medium and heavy trucks are included as large trucks. Large trucks are defined as all trucks with a gross vehicle weight rating (GVWR) of 10,001 pounds or more. This is the conventional GVWR threshold for trucks. It includes all trucks with at least two axles and six tires.

The purpose of this analysis is to identify crash events associated with the risk of serious injuries, here defined as fatal or A (incapacitating) injuries. Specific crash types are identified that pose a significantly higher probability of injury to the truck driver. Specific crash events that increase truck driver injury risk are also determined. The level of analysis is fairly high, since the desired detail on injury mechanisms—body regions injured, interior contact points and the like—simply is not available. It is not possible to determine injury mechanisms in the available accident data.

The findings here reinforce and update results from previous research reviewed above. Serious truck driver injury is associated with collisions with massive objects, either fixed objects such as bridge abutments or embankments or other large trucks or the ground, as in a rollover. Most truck crash involvements with another vehicle pose relatively low risk of serious injury to the truck driver because the other vehicle is typically a passenger vehicle that is much smaller than the truck. Single-vehicle crashes, in which the truck either rolls over or strikes a massive fixed object, or crashes involving another truck, account for the majority of serious injuries to the truck driver. Single-vehicle crashes and two-vehicle, truck-truck crashes account for about 75% of all truck driver fatalities and A injuries, though they are only 26% of all truck crash involvements. Moreover, three specific events—rollover, fire, and ejection—are found in almost two thirds of serious truck driver injuries, regardless of crash type.

An average of approximately 376,000 trucks are involved in traffic crashes every year. In these crashes, on average 5,485 persons are fatally injured and another 124,000 persons receive some sort of injury. As would be expected, most fatalities and injuries are suffered by occupants of passenger cars, light vehicles, or “non-motorists” such as pedestrians and bicyclists, rather than by truck occupants. Table 6 shows the average annual toll from traffic accidents involving trucks, separately for truck occupants and non-truck occupants. In this table, non-truck occupants include non-motorists, as well as drivers and passengers in automobiles, vans, and other light vehicles.

Table 6
Average Annual Injuries and Fatalities In Truck-Involved Crashes, 1995-1999

	Person location		
	Truck occupant	Not in truck	Total
Fatalities	744	4,741	5,485
Injuries	29,000	95,000	124,000
Total	30,000	99,000	129,000
	Row percentages		
Fatalities	13.6	86.4	100.0
Injuries	23.5	76.5	100.0
Total	23.1	76.9	100.0

Source: 1995-1999 TIFA and GES

Of the almost 5,500 people who are fatally injured each year; truck occupants account for 744, or about 13.6% of the fatalities. Approximately 124,000 people are injured to some degree, 29,000 of whom (23.5%) are truck occupants. While truck drivers and other occupants are “underrepresented” among the injured in crashes involving trucks, 30,000 annual casualties is a significant problem. The toll in deaths and injuries contribute to making truck driver one of the more dangerous occupations in the U.S.

Table 7 shows annual injuries to truck drivers, not all truck occupants. Since relatively few trucks have passengers, the driver of the truck will be the focus of the analysis from this point forward. About 633 truck drivers were fatally injured annually between 1995 and 1999. An additional 4,000 drivers suffered A injuries, 8,000 received B injuries, and 12,000 drivers had C injuries. There were an estimated 2,000 drivers with injuries of unknown severity, for a total of almost 27,000 truck drivers injured in traffic crashes annually.

Given the disparity in size, geometry, and structural stiffness between trucks and the other vehicles on the road, it is not surprising that injury risk to the truck driver is higher in crash types that do not include cars. Truck driver injury most often occurs when the truck strikes something relatively massive, either a roadside feature or the ground in a single vehicle crash, or another truck. Of the 633 annual driver fatalities, 410 or almost two-thirds occurred in single-vehicle crashes. Another 94 occurred in two-vehicle truck-truck crashes. There are about ten times more truck-car crashes than truck-truck crashes, but truck-truck crashes accounted for about half again as many truck driver fatalities, 94 to 65, as truck-car crashes.

Table 7
Average Annual Injuries to Truck Drivers, 1995-1999

Injury severity	N	%
Fatal	633	0.2
A injury	4,000	1.1
B injury	8,000	2.1
C injury	12,000	3.2
Injured, severity unknown	2,000	0.5
No injury	333,000	88.6
Unknown	19,000	5.1
Total	376,000	100.0

Source: 1995-1999 TIFA and GES

Single-vehicle crashes account for about 19% of crashes but 64% of truck driver injuries. There is an annual average of about 73,000 single-vehicle crashes, of which roughly 2,400 involve a fatal or A injury to the driver, and 23,000 some other injury. With rounding to the nearest 1,000 to account for the sampling error from the GES estimates, most of the cells would show zeros if frequencies were included. (See Table 8.)

Safety belts (seat belts) are widely understood to be the most effective injury prevention device available, but there are almost no data available on their use in the truck driver population, and data on safety belt use in crashes are likely biased. NHTSA in 1982 and again in 1991 monitored safety belt use at four weigh stations. About 6.3% of truck drivers were observed to use safety belts in 1982, and the observed proportion increased to about 56% in 1991. However, other than those observations, no estimates of belt use could be found.

Safety belt use coded in the crash data is likely to be biased, and the likely bias exaggerates estimates of effectiveness. Other than fatally- and seriously-injured drivers, for whom police officers can observe safety belt use directly, most belt use in crash data is self-reported. Given the increased emphasis on safety belt use, including laws mandating use in some jurisdictions and some trucking companies requiring them, it is likely that safety belt use is increasing. But it is also likely that drivers claim to have used a safety belt even if they did not, for the same reasons. Since belt use is self-reported for drivers with minor or no injuries, misreporting tends to over-report belt use for the uninjured, thus biasing upwards estimates of belt effectiveness.

Table 8
Average Annual Injuries to Truck Drivers by Crash Type, 1995-1999

	Crash Type				
Driver Injury	Single Vehicle	Truck-truck	Truck-car	More Than Two vehicles	Total
Fatal	410	94	65	63	633
A injury	2,000	0*	1,000	0*	4,000
B injury	4,000	1,000	2,000	1,000	8,000
C injury	5,000	1,000	5,000	1,000	12,000
No injury	58,000	21,000	229,000	24,000	333,000
Unknown	3,000	1,000	13,000	1,000	19,000
Total	73,000	25,000	250,000	28,000	376,000
	Column percentages				
Fatal	0.6	0.4	0.0	0.2	0.2
A injury	3.4	1.5	0.3	1.0	1.0
B injury	6.1	4.1	0.7	2.3	2.1
C injury	6.3	4.6	2.1	4.7	3.3
No injury	79.6	85.2	91.5	87.0	88.4
Unknown	4.0	4.1	5.3	4.8	5.0
Total	100.0	100.0	100.0	100.0	100.0

* Estimated fewer than 500
Source: 1995-1999 TIFA and GES

However, it is clear that belt use nearly eliminates ejection, a major risk factor in serious injury. Table 9 shows ejection for restrained and unrestrained drivers that suffered fatal or A injuries. Among the unrestrained, almost 23% were totally or partially ejected. In contrast, only 3.3% of restrained seriously injured drivers were partially ejected, and 0.1% was coded as totally ejected. In the case of belted ejected drivers, the cab of the truck was probably so heavily damaged that the seat was ejected along with the driver.

The ejection path is coded for truck drivers involved in fatal crashes. The ejection path provides important clues to cab structures that could be strengthened to keep the driver in the vehicle. Since virtually all ejected drivers suffer either fatal or A injuries, keeping the driver in the cab is an important first step. Unfortunately, the ejection path is not known for about 75% of ejected drivers. This is not surprising given the source of the data, but it warrants caution in interpreting the data. Of ejections where the ejection point is known, 34% of ejected truck drivers went out the windshield, and 30.7% were ejected through the side door. Among the partially ejected, 41.2% went through the side window, probably on the driver's side. Only 15.8% of the totally ejected went out the side window. Clearly, windshield retention and side doors remain targets for truck driver injury reduction.

Table 9
Ejection by Restraint Use
Truck Drivers with Fatal or A Injuries
1995-1999

	Unrestrained	Restrained
None	76.6	96.4
Partial	20.1	3.3
Complete	2.8	0.3
Unknown	0.5	0.1
Total	100.0	100.0

Source: 1995-1999 TIFA and GES

Overall, ejection increases the probability of driver fatality by almost 286 times, the risk of a fatal or A injury by 68.8 times, and the risk of a fatal, A or B injury by 28.5 times. Fire increases the risk of a truck driver fatality by 67.2 times, compared with the risk where no fire occurred. And rollover increases the risk of a driver fatality by almost 26 times, compared with no rollover.

Rollover, fire, and ejection are all strongly associated with truck driver injury. Over half (54.6%) of fatally injured truck drivers were involved in a rollover, as were 59.8% of drivers with A injuries. In contrast, only 2.2% of uninjured drivers rolled over. Only 0.2% of all truck drivers were ejected, but 31.5% of fatally injured drivers were ejected, and 6.5% of drivers with A injuries were ejected. In fact, no ejected driver in the five-year period covered by the data escaped injury. Similarly, fire in the vehicle also significantly increases the risk of a serious or fatal injury to a truck driver involved in a traffic crash, and is associated with a substantial number of fatalities. The truck caught on fire in 17.3% of truck involvements in which the driver died, while only 0.3% of all trucks involved in crashes experienced a fire.

Of course, rollover, fire, and ejection can occur together and in various combinations. Table 10 shows the permutations of rollover, fire, and ejection observed in the accident data, and the risk of a truck driver fatality or A injury associated with each. No rollover, fire, or ejection occurred in 95.2% of all truck crash involvements, and the probability of a fatal or A injury to a truck driver in those crashes was only 0.4%. However, if rollover only occurred, the risk rose to 14.1%. If only fire occurred, the risk also rose to 14.1%. And if the driver was ejected, without rollover or fire, his risk of fatal or A injuries was 54.4%. Ejection by itself is clearly the most serious event, but in combination with rollover, the truck driver's risk of fatal or A injuries increased to 85.1%. And in the five years covered by the data used here, no driver who suffered rollover, fire, and ejection, escaped either a fatal or A injury.

Table 10
Truck Driver Injury for Rollover, Fire, and Ejection

Crash event	Probability of fatal or A injury	Percent of fatalities and A injuries	Percent of all crash involve-ments
No rollover, fire, or ejection	0.4	35.2	95.3
Rollover only	14.1	49.7	4.3
Fire only	14.1	2.9	0.2
Ejection only	54.4	2.5	0.1
Rollover and fire	45.2	2.2	0.1
Rollover and ejection	85.1	6.9	0.1
Fire and ejection	96.1	0.3	0.0*
Rollover, fire, and ejection	100.0	0.2	0.0*

* less than 0.05%

Source: 1995-1999 TIFA and GES

Single-vehicle crashes also include crash types that present very low risk to the truck driver, such as collisions with pedestrians, bicyclists, and other non-motorists. Most of the non-fixed object crashes are collisions with parked vehicles or animals. These crash types represent only 0.1% and 0.9% of truck driver fatalities and A injuries, respectively. Note that the most harmful event was unknown in 8.6% of single-vehicle crashes and 14.4% of truck driver fatality or A injury crashes.

As might be expected, rollover is the primary harmful event in a single-vehicle crash in which a truck driver is killed or seriously injured. Rollover was the most harmful event in 63.1% of fatal or A injury single-vehicle crashes, compared with only 8.6% of the single-vehicle crashes in which the driver was uninjured, and 15.1% in all single-vehicle crashes. (See Table 11.)

Table 11
Percentage of Most Harmful Event in Single Vehicle Crashes by Truck Driver Injury

Most harmful event	Fatal/ A injury	Other injury	No injury	Unk.	Total
Rollover	63.1	44.4	8.6	4.1	15.1
Fire	2.0	0.4	0.8	0.0	0.7
Other non-collision	2.7	4.0	7.9	1.6	6.9
Ped./bike/ non-motorist	0.1	0.2	2.7	2.0	2.2
Train	2.5	1.3	0.4	0.0	0.5
Other non-fixed object	0.9	3.0	34.2	49.5	29.6
Hard object	6.9	10.3	7.8	2.7	7.8
Soft object	6.4	12.0	23.8	29.5	21.9
Other fixed object	1.0	2.4	7.5	6.0	6.6
Unknown	14.4	22.1	6.5	4.5	8.6
Total	100.0	100.0	100.0	100.0	100.0

Source: 1995-1999 TIFA and GES

There are other primary events posing an injury risk. These objects were categorized into "hard" and "soft" based on the amount of damage to the truck and the extent to which the objects were judged to be yielding in the event of a collision. "Hard" fixed objects include bridge piers and abutments, concrete barriers, culverts, and rock embankments. "Soft" fixed objects include light poles, trees, shrubbery, ditches and crash attenuators collision energy, while bridge abutments and rock embankments are essentially fixed. The goal of the classification was to separate "unyielding" from "yielding" objects. "Yielding" objects might be expected to slow the truck down when struck and to absorb some of the collision energy, while bridge abutments and rock embankments are essentially fixed. Trees constituted a very large fraction of the "soft" objects, which is somewhat problematic. Trees with a small diameter trunk are correctly included as "soft" in this classification, but larger trees are more likely to be relatively unyielding. Neither the TIFA data, which incorporate the FARS most harmful event variable, nor the GES data include information on trunk size. An arbitrary decision was made to include trees in the "soft" category. The most harmful event in 6.9% of truck driver fatalities and A injuries was a collision with a hard object, while 6.4% were collisions with "soft" objects.

Future Work

As stated earlier the objective of the current effort at UMTRI is to evaluate the benefits of implementing various occupant protection technologies and systems in trucks used on the US road system. In order to do this, the following tasks are currently being completed.

- Crash Modeling: Models of the various truck crashes will provide estimates of the forces and accelerations experienced by the truck structure and its occupants during collisions.
- Injury Models: Models of the mechanisms causing injury (cab crush, occupant striking windshield, roof, steering column etc.,) to truck occupants are also being developed. The models take into account the interior and will provide estimates of injury and fatality frequencies for the various crash types.
- Countermeasure evaluation: Injury and fatality frequencies will then be calculated in a similar manner after including the effect of applying occupant protection measures in the models, to obtain estimates of the improvement in occupant outcomes for each type.

CONCLUSION

Truck occupant protection systems have thus far received less attention than automobile passenger protection systems, but a number of recent studies are beginning to fill the gap in this area of vehicle crashworthiness research. These studies of motion of the occupant due to the crash accelerations and forces and the geometry of the truck cab cover a wide range of issues, including truck crash characteristics, occupant injury modes and mechanisms and most importantly occupant protection countermeasures.

A number of recent studies that take a comprehensive look at the truck occupant safety issue are also currently underway. Some of these studies include a comprehensive data collection effort in the United States supported by the National Highway

Traffic Safety Administration (NHTSA); the High Safety Vehicle (HSV) project in Europe involving partnership between several different users of truck transport including government bodies, research organizations, and commercial truck manufacturers and operators; and the Japan Automobile Manufacturers Associations efforts to improve truck crashworthiness. The results of these studies will be available in the near future and should provide much insight into the design of safer trucks.

Truck crash data and the literature show that a large proportion (~70%) of crashes in which truck occupants are significantly injured are single vehicle crashes, with truck-truck crashes being the second most dangerous to truck occupants. Rollover of the truck is the most significant injury-causing event involved in a majority (~60%) of these crashes. The important occupant injury mechanisms are ejection from the cab (involved in approximately one-third of all severe crashes), entrapment or crush, occupant striking interior surfaces (steering wheel, windshield, roof etc.) and post crash fire. The most promising countermeasures to improve the post crash safety of occupants include occupant restraints (seat belt and airbags). Most studies agree that restraint systems are the most effective of all protection countermeasures. Also, other effective measures are improved strength windshields and doors (to ensure occupant retention in the cab), more forgiving interior surfaces (energy absorbing steering column, padded interior surfaces etc.), and improved cab structure to provide occupant survival space.

Overall, it is clear that significant improvements in truck occupant safety can be achieved in the near future using a combination of currently developed and emerging occupant protection countermeasures.

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